

# NUCLEAR SHADOWING AND IN-MEDIUM PROPERTIES OF THE $\rho^0$ \*

T. FALTER, S. LEUPOLD AND U. MOSEL

*Institut fuer Theoretische Physik  
Universitaet Giessen  
D-35392 Giessen, Germany*

We explain the early onset of shadowing in nuclear photoabsorption within a multiple scattering approach and discuss its relation to in-medium modifications of the  $\rho^0$ .

The nuclear photoabsorption cross section is known to be shadowed at large energies, i.e.  $\sigma_{\gamma A} < A\sigma_{\gamma N}$ . This was at first interpreted as a confirmation of the vector meson dominance (VMD) model, which assumes that the photon might fluctuate into vector meson states with a probability of order  $\alpha_{em}$ . To give rise to shadowing, these hadronic fluctuations must travel at least a distance  $l_V$  that is larger than their mean free path inside the nucleus. This so called coherence length  $l_V$  can be estimated from the uncertainty principle

$$l_V \approx |k_\gamma - k_V|^{-1} = \left| k_\gamma - \sqrt{k_\gamma^2 - m_V^2} \right|^{-1} \quad (1)$$

where  $k_\gamma$  and  $k_V$  denote the momentum of the photon and the vector meson respectively and  $m_V$  is the vector meson mass.

Recent photoabsorption data<sup>1,2</sup> indicate an early onset of shadowing at  $E_\gamma \approx 1$  GeV. From (1) one sees that the lightest vector meson, e.g. the  $\rho^0$ , has the largest coherence length and therefore its properties determine the onset of the shadowing effect. This lead to the interpretation<sup>3</sup> of the low energy onset of shadowing as a signature of a decreasing  $\rho^0$  mass in medium since a decrease of  $m_\rho$  increases the coherence length  $l_\rho$ .

A quantitative description of the shadowing effect is possible within the Glauber model<sup>4</sup>. The nuclear photoabsorption cross section can be related via the optical theorem to the nuclear forward scattering amplitude. In order  $\alpha_{em}$  one finds the two contributions shown in Fig. 1. The left amplitude stems from forward scattering of the photon from one nucleon inside the nucleus. Summing over all nucleons this amplitude alone leads to the unshadowed cross section  $\sigma_{\gamma A} = A\sigma_{\gamma N}$ . Shadowing arises from the interference with the

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\*WORK SUPPORTED BY DFG AND BMBF.

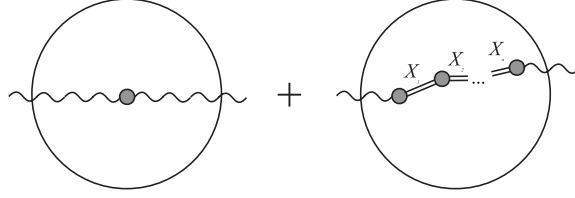


Figure 1. The two amplitudes that contribute to the nuclear forward scattering amplitude in order  $\alpha_{em}$ .

second amplitude in order  $\alpha_{em}$ . Here the photon produces some hadron  $X_1$  on one nucleon inside the nucleus. This hadron then scatters through the nucleus and finally into the outgoing photon which has the same momentum and energy as the incoming photon. Since we are dealing with the forward scattering amplitude and the nucleus has to be in its ground state after the last scattering event one usually assumes that it stays in its ground state during the whole multiple scattering process (multiple scattering approximation). One sees that, in principle, shadowing can be explained without the usage of VMD.

In the simple Glauber model one makes use of the eikonal approximation, assuming that all scattering events at high energies go predominantly into the forward direction. This limits the intermediate states  $X_i$  to hadrons which have the quantum numbers of the photon, e.g. the vector mesons. Neglecting off-diagonal scattering ( $VN \rightarrow V'N$  with  $V \neq V'$ ) and neglecting the widths of the vector mesons one gets for the total photon nucleus cross section

$$\sigma_{\gamma A} = A\sigma_{\gamma N} + \sum_{V=\rho,\omega,\phi} \frac{8\pi^2}{kk_V} \text{Re} \left\{ f_{\gamma V} f_{V\gamma} \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 n(\vec{b}, z_1) n(\vec{b}, z_2) \right. \\ \left. \times e^{iq_V(z_1 - z_2)} \exp \left[ -\frac{2\pi}{k_V} f_V \int_{z_1}^{z_2} dz' n(\vec{b}, z') \right] \right\}. \quad (2)$$

Here  $n(\vec{r})$  denotes the nucleon number density and  $f_{\gamma V}$  and  $f_V$  are the vector meson photoproduction and  $VN$  forward scattering amplitudes respectively. In our calculation<sup>5</sup> we also account for two-body correlations between the nucleons. In the derivation of (2) one has made an error of order  $A^{-1}$  by summing up infinitely many multiple scattering terms for the intermediate vector meson. This is equivalent<sup>5</sup> to the propagation of the vector meson in an optical potential, giving rise to an effective in-medium mass and width. The momentum transfer  $q_V = k - k_V$  in the phase factor arises from putting the vector meson on its mass shell. A large momentum transfer  $q_V$  causes a rapidly oscillating term in the integrand of (2) and reduces the shadowing

effect. Note that  $q_V$  is just the inverse of the coherence length  $l_V$  as can be seen from (1). We now relate the amplitudes  $f_{\gamma V}$  and  $f_V$  using VMD:

$$f_{\gamma V} = f_{V\gamma} = \frac{e}{g_V} f_V. \quad (3)$$

The  $\rho N$  forward scattering amplitude  $f_\rho$  is taken from dispersion theoretical analyses<sup>6,7</sup>. In the energy region that we are considering the real part of  $f_\rho$  is negative and of the same order of magnitude as the imaginary part, leading to an *increase* of the effective  $\rho^0$  mass in medium. Within VMD the negative real part also enters the photoproduction amplitude via (3). This enhances the shadowing effect and compensates the suppression due to the larger in-medium mass. In total one gets an increase of shadowing even with a positive mass shift of the  $\rho^0$  in medium. This can be seen from the left side of Fig. 2 where we show our results for the ratio  $\sigma_{\gamma A}/A\sigma_{\gamma N}$ . The calculation that includes the negative real part (solid lines) is in perfect agreement with the data. When the real part of  $f_V$  is neglected, as done in most other calculations, one gets the result represented by the dotted curves and clearly underestimates the shadowing effect for all nuclei. One even gets anti-shadowing below 2 GeV for Pb and 1 GeV for C.

In an improved model<sup>8</sup>, we explicitly sum over multiple scattering amplitudes where 1, 2, ...  $A$  nucleons participate in the scattering process. This avoids the error of order  $A^{-1}$  that occurs in the large  $A$  limit as described above. We also take the widths of the vector mesons into account and find that the main contribution to shadowing at low energies stem from light  $\rho^0$  mesons with masses well below the pole mass. These are favored by the nuclear form-factor because their production is connected with a small momentum transfer. This is in agreement with our qualitative understanding of shadowing, since light fluctuations have a larger coherence length. We also do not hold on to the eikonal approximation any longer. Dropping this restriction leads to a new contribution to the shadowing effect due to  $\pi^0$  mesons as intermediate states. Since these cannot be produced in the forward direction without excitation of the nucleus they do not contribute to shadowing at high energies. In the shadowing onset region, however, they give rise to 30% of the total shadowing effect in the case of C and 10% in the case of Pb as can be seen from the solid lines on the right side of Fig. 2. The dashed lines show the contribution from intermediate  $\rho$ ,  $\omega$  and  $\phi$  mesons. In total one again gets a good description of the shadowing effect.

We have presented a theoretical explanation for the early onset of shadowing as observed in nuclear photoabsorption. It can be explained by taking the negative real part of the  $\rho N$  forward scattering amplitude into account.

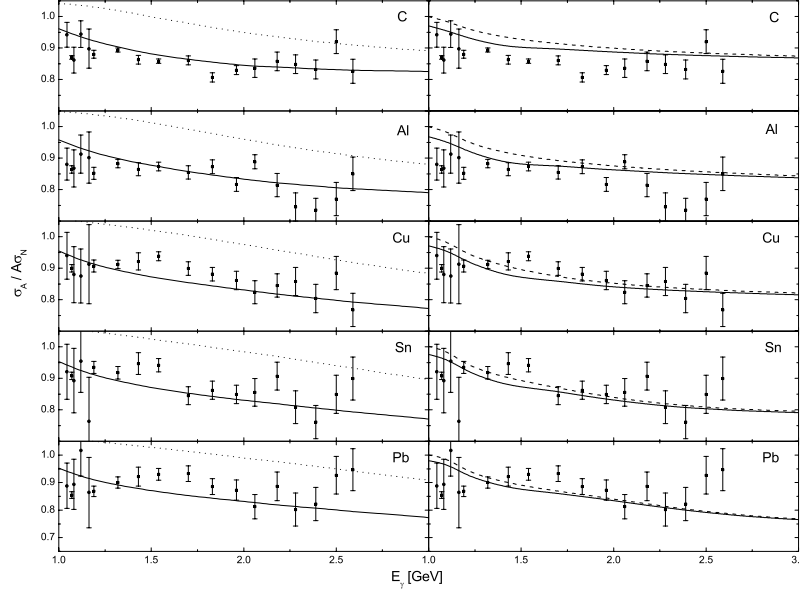


Figure 2. Calculated ratio  $\sigma_{\gamma A}/A\sigma_{\gamma N}$  plotted versus the photon energy  $E_\gamma$ . The *left* side shows the result of the simple Glauber model: with real part of  $f_\rho$  (solid lines),  $\text{Re}f_\rho = 0$  (dotted lines). The *right* side shows the result of our improved model: contributions from  $\rho$ ,  $\omega$  and  $\phi$  (dashed lines), including the contribution from intermediate  $\pi^0$  (solid lines).

This corresponds to an increase of the effective  $\rho^0$  mass in nuclear medium, in agreement with dispersion theoretical analyses. The major contribution to shadowing stems from light  $\rho^0$  with masses much smaller than the pole mass. In addition we find contributions from intermediate  $\pi^0$  to shadowing in the onset region.

## References

1. N. Bianchi *et al.*, Phys. Rev. C **54**, 1688 (1996).
2. V. Muccifora *et al.*, Phys. Rev. C **60**, 064616 (1999).
3. N. Bianchi *et al.*, Phys. Rev. C **60**, 064617 (1999).
4. T. H. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978).
5. T. Falter, S. Leupold and U. Mosel, Phys. Rev. C **62**, 031602 (2000).
6. V. L. Eletsky and B. L. Ioffe, Phys. Rev. Lett. **78**, 1010 (1997).
7. L. A. Kondratyuk *et al.*, Phys. Rev. C **58**, 1078 (1998).
8. T. Falter, S. Leupold and U. Mosel, Phys. Rev. C **64**, 024608 (2001).